The Industrial Revolution

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Chapter 3
The Industrial Revolution

The Industrial Revolution (roughly 1760 to 1850) was a turning point in world history, for it inaugurated the era of sustained economic growth. The Revolution was not the abrupt discontinuity that its name suggests but was the result of the transformations of the early modern economy discussed in the last chapter. The rate of economic growth achieved in the century after 1760 (1.5% per year) was very low by the standards of recent growth miracles in which GDP has grown by as much as 8–10% per year. However, Britain was continuously extending the world's technology frontier, and that is always slower going than catching up to the leader by importing its technology, which is how countries have grown very rapidly. Moreover, the great achievement of the British Industrial Revolution was that it led to continuous growth, so that income compounded to the mass prosperity of today.

Technological change was the motor of the Industrial Revolution. There were famous inventions like the steam engine, the machines to spin and weave cotton, and the new processes to smelt and refine iron and steel using coal instead of wood fuels. In addition, there were a host of simpler machines that raised labour productivity in unglamorous industries like hats, pins, and nails. There was also a range of new English products, many of which, like Wedgwood porcelain, were inspired by Asian manufactures.

In the 19th century, engineers extended the 18th-century mechanical inventions across the board. The steam engine was applied to transportation with the invention of the railway and the steamship. Power-driven machinery, whose use was initially restricted to textile mills, was applied to industry generally.

The question is: why was the revolutionary technology invented in England rather than the Netherlands or France or, for that matter, China or India?

Cultural and political context

The Industrial Revolution took place in a particular political and cultural context that was favourable to innovation, and that may help to explain it.

The English constitution has been a model for European liberals and modern economists alike. It was far from democratic: only 3–5% of the English could vote and even fewer of the Scots. Much power remained with the Crown – in particular, the power to make war and peace. While Parliament had a constitutional right to refuse funds for war, it never did.

The English constitution had many features that promoted economic growth, although they were not the ones stressed by modern economists, who emphasize restrictions on taxation and the security of property. Parliamentary supremacy actually resulted in the reverse. While French monarchs claimed to be absolute, they could not increase taxes without consent, and it was a crisis in public finances that precipitated the Revolution by forcing Louis XVI to convene the États généraux in 1789. The nobility in France were exempt from taxation, but the English Parliament introduced a land tax in 1693 that was imposed on peers as well as commoners. Most tax revenue, however, was raised from excise duties on consumer goods like beer and imports like sugar and tobacco. These taxes were borne primarily by

workers, who were not represented in Parliament. Parliament may have checked the Crown, but, in the absence of democracy, who checked Parliament?

In the event, the English state collected about twice as much per person as the French state and spent a larger fraction of the national income. It is arguable that these expenditures promoted economic growth. Most of the money was spent on the army and the navy. The former was occasionally directed abroad but was always available to maintain domestic order by suppressing assemblies opposed to machinery or in favour of democracy. The navy was directed to expand Britain's empire and promote the country's commerce. Even the workers gained from this since imperialism was the basis of the high-wage economy, which in turn led to growth by inducing labour-saving technical change. Had Louis XIV had the power to levy taxes, he might have advanced French prosperity by maintaining the French navy in a permanent state of readiness rather than enlarging or contracting it in response to the swing between war and peace.

Growth was also promoted by Parliament's power to take people's property against their wishes. This was not possible in France. Indeed, one could argue that France suffered because property was too secure: profitable irrigation projects were not undertaken in Provence because France had no counterpart to the private acts of the British Parliament that overrode property owners opposed to the enclosure of their land or the construction of canals or turnpikes across it. What the Glorious Revolution meant in practice was that the 'despotic power' of the state that 'was only available intermittently before 1688 . . . was always available thereafter'.

In addition to a favourable political system, the Industrial Revolution was sustained by the emerging scientific culture. The Scientific Revolution of the 17th century led to a handful of discoveries about the natural world that were applied by inventors in the 18th. In addition, the success of natural philosophy lent

credibility to the scientific method, that is, the view that the world is governed by laws that can be discovered by observation and applied to the improvement of human life. Newton's model of the Solar System was the greatest achievement, and it inspired a reorientation of upper-class ideas about religion and nature.

How much popular culture shared in this reorientation is an open question. There are important examples of working-class inventors adopting the Newtonian model. John Harrison, for instance, was lent a copy of Saunderson's lectures on natural philosophy, a Newtonian tract, by a clergyman, and made a copy of it. Did this early interest in Newton dispose Harrison to invent the chronometer? On the other hand, there was continued popular enthusiasm for witchcraft, which was the medieval alternative to science. It is likely that more people believed in witchcraft than in Newton's laws of motion. John Wesley's preaching was attracting millions of followers, and he was of the view that the 'giving up of witchcraft is, in effect, giving up the Bible'.

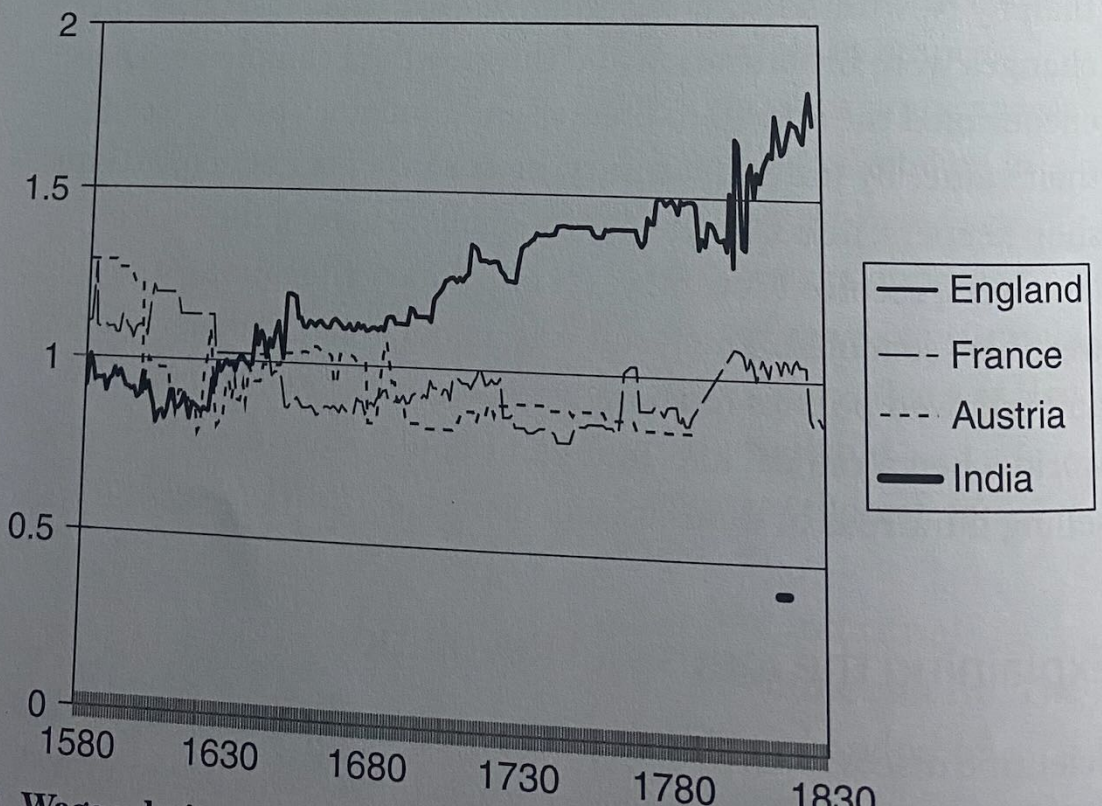
Popular culture was more directly transformed by social changes than by Newton's *Principia Mathematica*. The most powerful changes were urbanization and the growth of commerce. They encouraged the spread of literacy and numeracy by increasing their value. By the 18th century, most sons of craftsmen, artisans, shop keepers, and farmers, and a smaller share of the sons of labourers, received several years of primary education. Many girls were also schooled. The result was a public that read newspapers and followed politics to an unprecedented degree. It was a new world when a radical like Tom Paine could achieve celebrity by selling hundreds of thousands of copies of *The Rights of Man*.

Explaining the Industrial Revolution

Scientific discoveries were known across Europe, and upper-class enthusiasm for natural philosophy was universal. These cultural developments, therefore, cannot explain why the Industrial

Revolution was British. Instead, the explanation lies in Britain's unique structure of wages and prices. Britain's high-wage, cheap-energy economy made it profitable for British firms to invent and use the breakthrough technologies of the Industrial Revolution.

In Chapters 1 and 2, we saw that wages in Britain were sufficiently high for most people to eat bread, beef, and beer, instead of subsisting on oatmeal. More to the point, so far as technology is concerned, British wages were high relative to the price of capital (Figure 7). In the late 1500s, the wage rate relative to the price of capital services was similar in southern England, France, and Austria, which are representative of continental Europe. By the middle of the 18th century, however, labour relative to capital was 60% more expensive in England than on the continent. In the early 19th century, which is the first time a comparison can be made with Asia, labour was even cheaper relative to capital in India than it was in France or Austria. The incentive to mechanize production was correspondingly less in India.



7. Wage relative to price of capital services

It was the same story with energy. Britain, especially on the coal fields in the north and in the midlands, had the cheapest energy in the world. Consequently, energy was much cheaper compared to labour in Britain than it was anywhere else.

As a result of these differences in wages and prices, businesses in England found it profitable to use technology that saved on expensive labour by increasing the use of cheap energy and capital. With more capital and energy at their disposal, British workers became more productive – the secret of economic growth. In Asia and Africa, the cheapness of labour led to the opposite result.

The cotton industry

Eric Hobsbawm famously wrote: 'Whoever says Industrial Revolution says Cotton.' From tiny beginnings in the mid-18th century, the industry grew to be Britain's largest, accounting for 8% of GDP in 1830 and 16% of British manufacturing jobs. Cotton was the first industry to be transformed by factory production. The growth of cotton led to the explosive growth of Manchester and many smaller cities in the north of England and Scotland. Britain's expansion came at the expense of India, China, and the Middle East. When these countries eventually began to re-industrialize, cotton was one of the first industries they turned to.

In the 17th century, China and India had the world's largest cotton industries. Bengal, Madras, and Surat shipped cotton cloth across the Indian Ocean and as far as West Africa. Cotton was also produced in small centres across Asia and Africa. The various East Indies companies began to ship cotton calicoes and muslins to Europe in the late 17th century where they successfully competed against linen and wool, the principal European textiles. Cotton was so successful that France prohibited its import in 1686, and the English restricted its domestic consumption. However, there was a large export market in West Africa, where cotton cloth was

bartered for slaves. In this market, English cloth competed against Indian cloth.

International competition was the spur that led to the mechanization of cotton spinning. The finer the cotton, the more time it took to spin. Wages were so high in England that competition with India was only possible in the coarsest fabrics. There was a large market in finer fabrics, but England could only compete if machines were invented to reduce labour. The stakes were considerable: in 1750, Bengal spun about 85 million pounds of cotton per year, while Britain managed only 3 million. There were numerous attempts to mechanize production. James Hargreaves' spinning jenny, developed in the mid-1760s, was the first commercially successful machine, followed closely by Richard Arkwright's water frame. Samuel Crompton's mule, invented in the 1770s, married the jenny and the water frame (hence its name) and became the basis of mechanical spinning for a century.

These machines owed nothing to scientific discoveries. None involved great conceptual leaps; instead, they required years of experimental engineering to come up with designs that worked reliably. Thomas Edison's remark that 'invention is 1% inspiration and 99% perspiration' is on the mark for the cotton industry.

The crux in explaining why the Industrial Revolution was invented in Britain is, therefore, explaining why British inventors spent so much time and money doing R&D (Research and Development, that is, Edison's 'perspiration') to operationalize what were often banal ideas. The key is that the machines they invented increased the use of capital to save labour. Consequently, they were profitable to use where labour was expensive and capital was cheap, that is, in England. Nowhere else were the machines profitable. That is why the Industrial Revolution was British.

Cotton yarn was manufactured in three stages. First, the bales of raw cotton were broken open and the dirt and debris removed.

Second, the cotton was carded, that is, the strands of cotton were aligned into a loose strand called a roving by dragging the cotton between cards studded with pins. Third, the roving was spun into yarn. Before machines, the whorl and drop spindle was used to make fine yarn, while the spinning wheel made coarse yarn. In each case, the roving was stretched to thin it, then twisted to strengthen it, and, finally, the yarn was wound on a spindle to send to weavers.

All of these stages were mechanized, and, indeed, Richard Arkwright's greatest achievement was to design a mill (Cromford Mill No.2) in which machines were laid out in a logical sequence, and which became the model for the early cotton mills in Britain, the USA, and the continent. Spinning was the crux of the problem, and inventors had worked on it since at least the 1730s. Lewis Paul and John Wyatt were on the right track in the 1740s and 1750s with their system of roller spinning, but their mill in Birmingham always lost money. James Hargreaves' spinning jenny, invented in the 1760s, was the first commercially successful spinning machine. It elaborated the spinning wheel by running many spindles off one wheel and using draw bars and linkages to mimic the movements of the spinner's hands. Arkwright employed clockmakers for five years in order to perfect his water frame that used rollers. With roller spinning, the roving was stretched by pulling it through successive pairs of rollers, which, like mangles, dragged the cotton forward. Each pair of rollers moved faster than the previous, so they lengthened and thinned the yarn by pulling against each other.

Crompton's mule was the last great spinning machine. It combined the draw bars of Hargreaves' jenny with the rollers of Arkwright's water frame to make a machine that could spin yarn far finer than any of the other machines. The jenny and the water frame made England competitive with Indian producers in coarse yarn; the mule made England the low-cost producer in fine yarn as well.

The economics of these machines were similar. All of them reduced the hours of labour needed to produce one pound of yarn. At the same time, they increased the capital required per pound. As a result, the cost saving from mechanical spinning was higher where labour was more expensive. In the 1780s, the rate of return to building an Arkwright mill was 40% in England, 9% in France, and less than 1% in India. With investors expecting a 15% return on fixed capital, it is no surprise that about 150 Arkwright mills were erected in Britain in the 1780s, 4 in France, and none in India. Relative profitability was similar with the spinning jenny, as was the result – 20,000 jennies were installed in England on the eve of the French Revolution, 900 in France, and none in India. There was no point in spending much time or money to invent mechanical spinning in France or India since it was not profitable to use it there.

The situation did not remain like this, which is why the Industrial Revolution spread to other countries. Arkwright's mills created an integrated series of machines that cut costs by more than Hargreaves' jenny. Crompton's mule cut the cost of spinning fine yarn. A long list of inventors improved the mule over the next half century. They economized on capital as well as on labour. By the 1820s, improved cotton machinery could be profitably installed on the continent, and by the 1850s, it proved profitable to install even more improved machinery in low-wage economies such as Mexico and India. By the 1870s, factory cotton production began to shift into the Third World.

The steam engine

The steam engine was the most transformative technology of the Industrial Revolution since it allowed mechanical power to be used in a wide range of industries as well as in railways and ocean ships.

Steam power was a spin-off of the Scientific Revolution. Atmospheric pressure was one of the hot topics of 17th-century

physics. It was investigated by famous scientists across Europe, including Galileo, Torricelli, von Guericke, Huygens, and Boyle. By the middle of the century, Huygens and von Guericke had shown that, if a vacuum was created in a cylinder, then the pressure of the atmosphere would force a piston into it. In 1675, the Frenchman Denis Papin used this idea to make a crude, proto steam engine. A practical engine was completed by Thomas Newcomen in 1712 in Dudley, after 12 years of experimentation. Newcomen's engine involved boiling water to make steam, filling a cylinder with it, and then injecting cold water into the cylinder to condense the steam so that the pressure of the atmosphere depressed a piston into the cylinder. The piston was connected to a rocker beam that raised a pump as the piston was depressed.

The steam engine emphasizes the importance of economic incentives in inducing invention. The science of the engine was pan-European, but the R&D was conducted in England because that was where it paid to use the steam engine. The purpose of the Newcomen engine was to drain mines, and Britain had many more mines than any other country due to the large coal industry. In addition, the early steam engines burned vast quantities of coal, so they were cost-effective only where energy was cheap. John Theophilus Desaguliers wrote in the 1730s that the Newcomen engines were 'now of general use … in the Coal-Works, where the Power of the Fire is made from the Refuse of the Coals, which would not otherwise be sold'. They were scarcely used anywhere else. Despite the scientific breakthroughs, the steam engine would not have been developed had the British coal industry not existed.

Steam power became a technology that could be applied to many purposes and used around the world, but only after the engine was improved. This was not accomplished before the 1840s. Engineers like John Smeaton, James Watt, Richard Trevithick, and Arthur Woolf studied and modified the engine, reducing its energy requirements and smoothing its delivery of power. Coal

consumption per horse power-hour of power was cut from 44 pounds in the Newcomen engines of the 1730s to one pound in the triple expansion marine engines of the late 19th century. The genius of British engineering undid the country's competitive advantage by improving its technology to the point that it could be profitably used around the globe. This allowed the Industrial Revolution to spread abroad and the whole world to industrialize.

Continuing invention

The greatest achievement of the Industrial Revolution was that the 18th-century inventions were not one-offs like the achievements of earlier centuries. Instead, the 18th-century inventions kicked off a continuing stream of innovations.

Cotton continued to be a focus of effort. While the 18th-century inventions had turned spinning into a factory system, weaving was still done on hand looms in cottages. This was changed by the Reverend Edmund Cartwright, who spent decades and wasted his fortune perfecting a power loom. He was inspired by automatons like Jacques de Vaucanson's mechanical duck that wowed the court in Versailles by flapping, eating, and defecating! (Voltaire quipped: 'Without Vaucanson's duck, you have nothing to remind you of the glory of France.') If a mechanism could poop like that, couldn't it also do useful work? Cartwright thought so and patented his first loom in 1785 and an improved version in 1792. It was not commercially viable, however. Many inventors improved it piecemeal. By the 1820s, the power loom was displacing hand looms in England, but they continued in use until the 1850s. The power loom greatly increased capital costs while reducing labour costs, so its adoption was sensitive to factor prices as well as the relative efficiency of the two methods. It is singularly important that the power loom was taken up more rapidly in the USA than it was in Britain. By the 1820s, wages were already higher in the USA, and the pattern of technological innovation reflected that difference.

Cotton also led the way in the application of steam power to factories. Experiments had been made earlier, of course. In 1784, Boulton and Watt invested in the Albion Flour Mill, the first large-scale steam-powered factory, to promote their engines. The next year, steam was applied to a cotton mill for the first time. However, most factories were driven by water power until the 1840s. It was only then that the fuel consumption of steam engines had dropped sufficiently to make them a cheaper source of power. After that, the use of steam to power industry expanded continuously.

Steam power also revolutionized transportation in the 19th century. Everyone who invented a high-pressure steam engine (Cugnot, Trevithick, Evans) used it to power a land vehicle, but they were all unsuccessful since they could not negotiate the unpaved roads. One solution was to put the engine on rails. Coal and ore had long been hauled in carts rolling on primitive wooden rails laid in mines. In the 18th century, iron rails replaced wood, and the lines were extended. In 1804, Richard Trevithick built the first steam locomotive for a railway at the Penydarren Ironworks in Wales. From then on, colliery railways became the testing ground for steam locomotives. The 26-mile Stockton and Darlington Railway (1825) was planned as a coal railway but showed there was money to be made in carrying general freight and passengers. The first general-purpose railway was the 35-mile Liverpool and Manchester Line, opened in 1830. It was a great success and set off a frenzy of railway promotion in Britain. Almost 10,000 kilometres of track were open by 1850, and 30 years later, the network reached 25,000 kilometres.

Steam power was also applied to water travel – another way of avoiding bad roads! Invention was international from the start. The first working vessels were French – the *Palmipède* (1774) and *Pyroscaphe* (1783) – and the first commercially successful ship was Robert Fulton's *Clermont*, which plied the Hudson River from

1807. Two years later, John Molson, the Canadian brewer, sailed steamships on the St Lawrence River using engines built in Trois-Rivière, Québec.

By the middle of the 19th century, steam was displacing sail in ocean transportation. Britain became the centre of world shipbuilding in view of its pre-eminence in iron and engineering. Brunel's *Great Western* (1838) marked a breakthrough, for it established that a ship could carry enough coal to cross the Atlantic, and his *Great Britain* (1843) was the first ship to be built of iron and to use a propeller instead of paddle wheels. It took another half century, however, for steam to vanquish sail. The reason was that ships still had to carry their own coal, so they lost much of their cargo space on long voyages. The first routes to shift to steam were consequently short. As the coal requirements of steam engines were reduced, ships could sail longer distances with the same amount of coal, and the distance for which steam could undercut sail lengthened. The last routes to fall were those from China to Britain where clipper ships survived until the end of the 19th century.

Steam power is an example of a general-purpose technology (GPT), that is a technology that can be applied to a variety of uses. Other GPTs include electricity and computers. It takes decades to develop the potential of GPTs, so their contribution to economic growth takes place long after their invention. That was certainly true for steam. As late as 1800, almost a century after Newcomen's invention, steam power made only a minute contribution to the British economy. By the middle of the 19th century, however, the potential of steam was finally being realized as it was applied widely to transportation and industry. Half of the growth of labour productivity in Britain in the mid-19th century was due to steam. This long-run pay-off is an important reason that economic growth continued through the century. Another reason was the growing application of science to industry, which we will consider in the next chapter.